



## King's Research Portal

DOI:

[10.1109/ICC.2016.7511106](https://doi.org/10.1109/ICC.2016.7511106)

*Document Version*

Peer reviewed version

[Link to publication record in King's Research Portal](#)

*Citation for published version (APA):*

Holland, O. D., Aijaz, A., Ping, S., Wong, W. S., Mack, J., Lam, L., & de la Fuente, A. (2016). Aggregation in TV white space and assessment of an aggregation-capable IEEE 802.11 white space device. In *IEEE International Conference on Communications (ICC) 2016* Institute of Electrical and Electronics Engineers Inc..  
<https://doi.org/10.1109/ICC.2016.7511106>

### **Citing this paper**

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

### **General rights**

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Research Portal

### **Take down policy**

If you believe that this document breaches copyright please contact [librarypure@kcl.ac.uk](mailto:librarypure@kcl.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.

# Aggregation in TV White Space and Assessment of an Aggregation-Capable IEEE 802.11 White Space Device

Oliver Holland, Adnan Aijaz,  
Shuyu Ping, Stan Wong  
King's College London  
London, UK  
{oliver.holland, adnan.aijaz,  
shuyu.ping, stan.wong}@kcl.ac.uk

Jane Mack, Lisa Lam  
InterDigital Communications, Inc.  
Melville, NY, USA  
{jane.mack, lisa.lam}@interdigital.com

Alejandro de la Fuente  
Universidad Carlos III de Madrid  
Madrid, Spain  
afuente@tsc.uc3m.es

**Abstract**—TV White Spaces (TVWS) has taken a major step forward with the UK regulator Ofcom initiating a pilot of the technology and associated procedures in the UK, and TVWS rules being harmonized at the European level. This paper considers some aspects of our trial within the Ofcom TV White Spaces Pilot, namely, investigation of aggregation in TVWS and the deployment and testing of IEEE 802.11 white space devices that are capable of aggregating up to 4 TV channels, contiguously or non-contiguously. Our trial is the only deployment of these devices, developed at InterDigital in the USA, within the Ofcom TV White Spaces Pilot. This paper discusses the specifics of the InterDigital devices, including their design and capabilities. Further, results are presented highlighting what is possible in TVWS through contiguous aggregation. These results are achieved through per-channel allowed EIRP and capacity analyses based on feedback from a TVWS database within the Ofcom Pilot, using TVWS functionality developed at King's College London. Additional results outline the added benefit of optimal non-contiguous aggregation. Finally, this paper performs a like-for-like comparison of the performance of the InterDigital devices against what is theoretically possible in TVWS through capacity analyses using feedback from the TVWS database.

**Keywords**—TV white space, geolocation databases, field trials, spectrum aggregation, spectrum sharing

## I. INTRODUCTION

Progress in TV White Spaces (TVWS) has been driven forward initially by regulatory steps and deployments of White Space Devices (WSDs) in the USA [1]. Europe is now following with the finalization of rules and testing of TVWS technology on a large scale [2]–[6]. This is driven by the UK regulator Ofcom's work and instantiation of a large pilot of WSDs and the underlying enabling technology [5]. All trials in this pilot must operate under Ofcom's prospective rules for WSDs, reflected in ETSI EN 301 598 [4].

We are running a major trial within the Ofcom TV White Spaces Pilot. As well as testing a range of types of WSDs and deployment scenarios, this work includes several research aspects, such as study of solutions for aggregation of TVWS resources/links, and aggregation of TVWS resources/links with other non-TVWS resources/links. The research on aggregation of TVWS resources has been greatly facilitated by InterDigital, USA, creating and loaning WSDs which include the capability of aggregating multiple IEEE 802.11 links in

different TVWS channels [7], [8], and providing training and advice on the use of this experimental equipment.

This paper focuses on aggregation in TVWS. In particular, it demonstrates: (i) what is possible in TVWS through contiguous aggregation, as would be achieved by a single radio on a WSD with, e.g., an OFDM waveform, (ii) the additional gain through non-contiguous aggregation, as might be achieved with multiple radios on a WSD or through the use of a novel waveform such as Filter-Bank Multi-Carrier, RB-F-OFDM, Windowed OFDM or UW DFT-s-OFDM, and (iii) a direct comparison of the performance of the InterDigital system for non-contiguous aggregation with what is achieved via similar capacity analyses at the same location/scenario.

This paper is structured as follows. In Section II we introduce the InterDigital WSDs, including their purposes, capabilities, and logical aspects such as their Geolocation Database (GLDB) communications and commands to the radios from a cognitive radio channel selection procedure that receives input from the GLDB. In Section III, we describe our methodology for assessment of aggregation in TVWS, and give our assessment of the performance of such aggregation. In Section IV, we discuss some of our performance assessments of the InterDigital devices and compare those with what is theoretically possible as an upper bound. In Section V, we conclude the paper, also discussing the importance of aggregation in TVWS and future systems.

## II. USE OF THE INTERDIGITAL TV WHITE SPACE DEVICES

The InterDigital Dynamic Spectrum Management (DSM) TVWS IEEE 802.11 Demonstration Platform [7], [8], which has been deployed at King's College London, is referred to as the "WSD" in this paper. It is designed to research, experiment with and demonstrate an implementation of a certified 802.11 protocol stack that has been modified to operate in TVWS. This system is capable of aggregating up to 4 contiguous or non-contiguous TVWS channels in order to maximize capacity, and was designed to meet the Federal Communications Commission (FCC) requirements for license-exempt TVWS operation [1]. However, in collaboration with the expertise on the Ofcom TVWS framework of King's College London, the platform has been adapted to meet the operational requirements of the UK regulator Ofcom for usage in the UK, noting that these requirements have also been

adopted on the European level through the ETSI EN 301 598 Harmonized European Standard. This adaptation has enabled certification of the devices for UK use, and participation of the devices in the Ofcom TV White Spaces Pilot.

These WSDs are typically deployed for experimentation with means of providing backhaul for wireless access in TVWS. However, one key observation of our work within the Ofcom Pilot has been that, in the UK and likely in other cases in Europe with similar Digital Terrestrial Television (DTT) deployment characteristics, TVWS seems perhaps most beneficial for below-rooftop and indoor receiver deployments, particularly if the intention is to receive a low signal level [9]. Hence, the work in this paper addresses such cases, where the actual deployments of the WSDs considered here are indoor at the Institute of Psychiatry in the Denmark Hill campus of King's College London. This location was chosen because of its good TVWS availability among the locations authorized to King's College London within the Ofcom Pilot, and also because of the somewhat typical nature of its building characteristics.

Figure 1 presents the structure under which the WSDs are deployed in our testing. The devices, with the High Power Module (HPM) deployed (which adds 30 dB amplification) produce an output of 26 dBm in a single channel. With an antenna gain of 10dBi through the utilized antennas, this increases to the 36 dBm maximum EIRP limit under the UK/EU framework. In multi-channel mode, this value per channel drops as each additional channel is added, and for the 4-channel case investigated in this paper the output power is 20-21 dBm, giving 30-31 dBm EIRP. Moreover, as is the case for all devices currently deployed within the Ofcom TV White Spaces Pilot, the InterDigital WSDs do not adapt their EIRP in response to the allowed EIRP values issued by the GLDBs under the UK/EU implementation. They simply compare their fixed EIRP with the power values allowed per channel as returned by the GLDB, and only allow transmission on a given channel if that fixed EIRP is less than or equal to the allowed power on that channel. An optimal WSD under the UK/EU framework should, however, vary its transmission power in response to the feedback from the GLDB in order to maximize TVWS availability and operate in more channels or locations.

Referring to Figure 2, each WSD comprises a 802.11 MAC/PHY development board, a Digital Baseband (DBB) board incorporating a Sensing Toolbox (STB), and two wideband digital radio boards. Each radio board can cover a bandwidth of up to 48 MHz, and is capable of transmitting on up to 4 contiguous or non-contiguous channels individually or combined, and filtering emissions in between the utilized channels such that emission class limits are not violated.

One key innovative aspect of the devices is the inclusion of the STB, which allows investigation and experimentation with spectrum sensing capabilities supporting the white space radios. This solution enables sensing of Digital/Analog TV and Microphone signals, and has been utilized for such purposes in the US. However, this capability is currently disabled, as DTT and PMSE avoidance is achieved entirely by GLDB means under the UK/EU rules.

Aggregation by the WSDs is done at the MAC layer, which allows system flexibility by tailoring MAC Protocol Data Units (PDUs) to fit the channel quality and bandwidth of

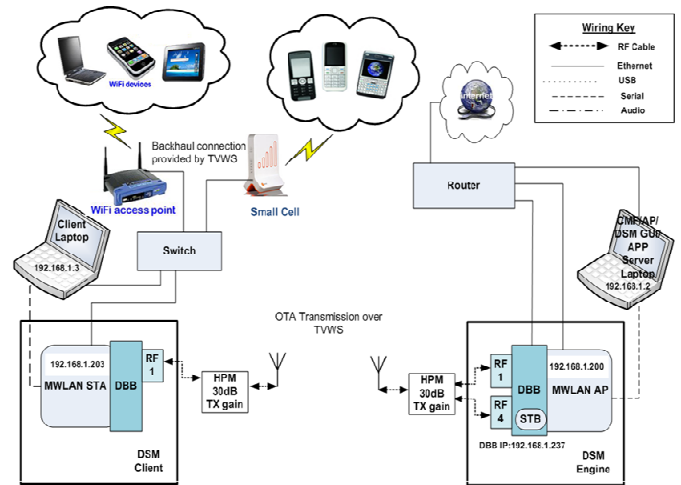


Fig. 1. Utilized deployment set-up for the InterDigital equipment.

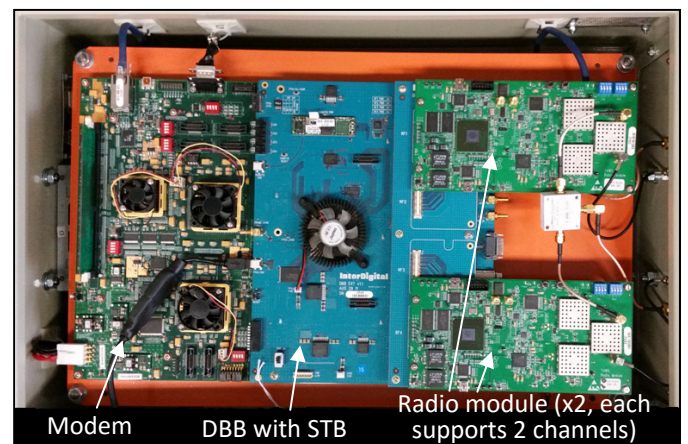


Fig. 2. The InterDigital DSM IEEE 802.11 in TV white spaces experimentation platform.

each PHY channel. Furthermore, at transmission time, if one or more channels are busy, only the MAC PDUs associated with the busy channels are deferred, while MAC PDUs associated with other channels are transmitted.

The InterDigital equipment on the Access Point (AP) side implements an application known as the Channel Management Function (CMF). This interacts with the Ofcom web-listing of GLDBs in order to choose a Ofcom-approved GLDB, then interacts with the chosen GLDB. It also instructs the sensing capabilities of the device, and performs sensing if desired via the DBB/STB. Selecting among the best of the available channels and powers in terms of observed interference from other devices could be one application of this. Depending on configuration and regulatory compliance, the WSD can also perform throughput testing on allowed channels as returned by the GLDB, before choosing a channel for transmission.

The CMF can base its channel ranking and selection on the information from the GLDB, sensing, and quality metrics. In the UK, this ranking might use sensed interference in channels, channel frequency and GLDB channel EIRPs. In the US, throughput testing could also be used, however GLDB EIRPs would all be the same and therefore would not be used.

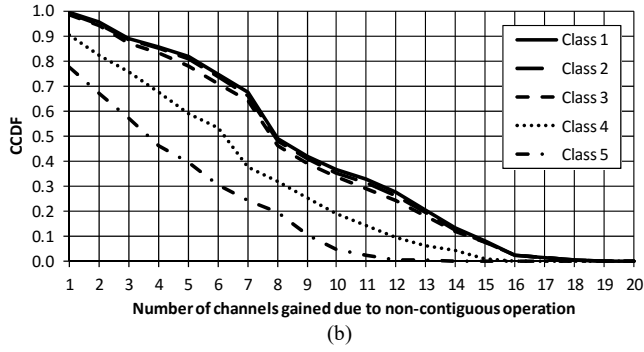
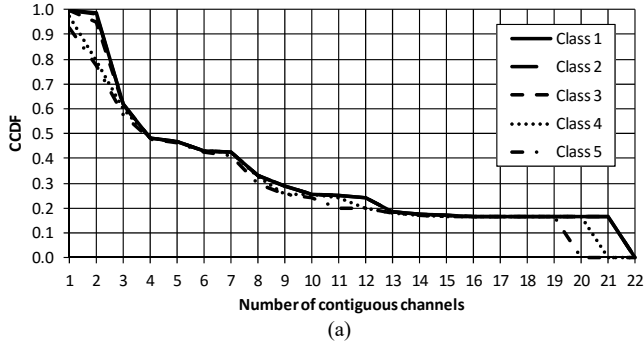


Fig. 3. CCDFs of channel availability for the Mobile Broadband scenario for all Ofcom/ETSI mask classes: (a) Contiguous-only aggregation, and (b) additional channel availability achieved through non-contiguous aggregation.

TABLE I: SCENARIO CONFIGURATION

Scenario	Tx/Rx Height (m)	Path loss	Model-specific parameters
Mobile Broadband	Tx 30, Rx 1.5	Hata urban, large city	Allowed EIRP $\geq 30$ dBm for channel availability, Tx distance 2km
Indoor Wireless	Tx 1.5, Rx 1.5	Yamada indoor [10]	Same floor; Tx distance and number walls as in Figure 6

### III. AGGREGATION CHANNEL AVAILABILITY AND CAPACITY ASSESSMENTS

First we broadly assess the performance of aggregation in TVWS. We have implemented a WSD as part of our participation in the Ofcom Pilot at King’s College London, and we use that to query a Ofcom-qualified GLDB and transform/process the responses to obtain observations on performance. In addition to available channel assessments, we undertake capacity analyses using loss parameters indicated in Table 1. Results are all sampled/processed in steps of 0.01 degrees both in latitude and longitude, for the London, UK, “M25” area as mapped later in Figure 5. This corresponds to 2,775 samples in total over that area for each assessment.

First, for the Mobile Broadband scenario in Table 1, Figure 3(a) considers channel availability under contiguous aggregation as a baseline. Results here reflect the best case of every possible combination of contiguous channels for each location, where the EIRP spectral density of the WSD is reduced to the equivalent of the minimum of allowed EIRPs for the contiguous channels to not violate the spectral density limit in any channel—assuming a spectrally “flat” waveform.

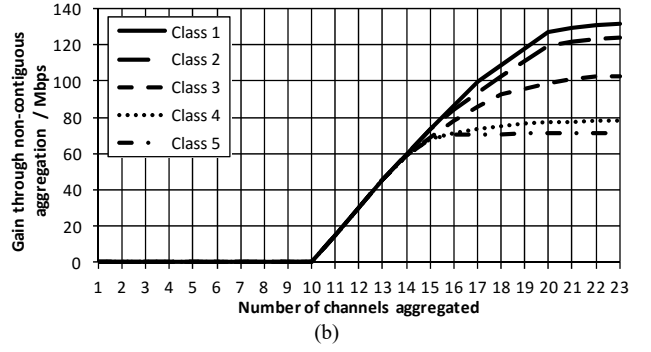
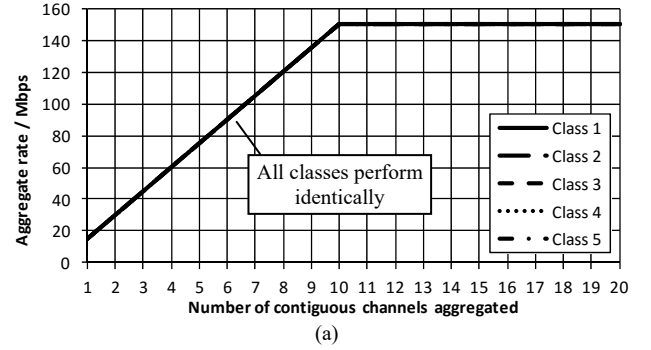


Fig. 4. Achievable capacity for the Mobile Broadband scenario at the King’s College London Denmark Hill campus: (a) Contiguous-only aggregation, and (b) additional capacity gained through non-contiguous aggregation.

Results in Figure 3(a) indicate that all spectrum mask classes under the UK/EU framework perform relatively similarly, if 3 or more contiguous channels are aggregated. Moreover, only 60% of locations are able to aggregate those 3 or more channels at 30 dBm allowed EIRP or above. This is an important observation given that a number of key communication systems currently deployed typically assume a 20 MHz bandwidth, requiring the utilization of 3 contiguous channels in TVWS if an alternative TVWS system is to be developed with comparable performance. Moreover, if the communication system strives for Classes 1-3, there is over 98% probability of having at least 2 contiguous channels available—a bandwidth of 16 MHz, able to comfortably accommodate a 10 MHz LTE transmission (although likely not a 15MHz transmission, due to sideband roll-off).

Results in Figure 3(b) clearly show the immense benefit of non-contiguous aggregation in terms of additional channel availability. For example, if a Class 1-3 device is deployed, it is almost certain that there will be at least one additional channel made available through non-contiguous aggregation, and there is an 80% probability that there will be at least 5 additional channels made available. Another observation here is that Classes 1-3 achieve relatively similar performance gains through non-contiguous aggregation, whereas Classes 4 and 5 take respectively bigger performance hits in terms of additional gain through non-contiguous aggregation.

The discussion here justifies the benefits of building WSDs capable of non-contiguous channel aggregation, such as the WSDs assessed in this paper. These benefits are further clear through an assessment of the capacity achieved at the King’s College London Denmark Hill campus in Figure 4. Noting that this location has good white space availability





Fig. 5. Availability of 4 contiguous channels with at least 30 dBm allowed Tx EIRP, Ofcom/ETSI Class 3 device, London “M25” area, Mobile Broadband scenario. Light areas are where 4 contiguous channels are available.

hence 10 channels already being usable contiguously, non-contiguous aggregation makes around an additional 8 channels available for a good class of WSD, achieving around 100 Mbps capacity gain. Such benefit is further emphasized by referring to the results in Figure 5, where aggregating 4 contiguous channels it is clear that large areas of London cannot be used. Alternatively, aggregating non-contiguously gives at least 4 channels being usable in over 99% of this area.

#### IV. AGGREGATION PERFORMANCE OF THE INTERDIGITAL SYSTEM

Next we perform additional theoretical capacity analyses and compare with similarly-configured experiments to assess the performance of the WSDs. Results here are for the “Indoor Wireless” scenario in Table 1, noting that our theoretical (Shannon) capacity analyses are based on measured links’ propagation and noise-plus-interference, and the path loss model in Table 1 is only used for later discussion. Similarly to Section III, results are obtained by querying a real GLDB and using the responses to perform our capacity analyses. Moreover, although each TV channel in the UK is 8 MHz bandwidth, we set bandwidth per channel for our capacity analyses to 5 MHz. This mirrors the WSDs, which transmit a 5 MHz signal in each aggregated channel.

Figure 6 depicts the 4 links tested at the King’s College London, Denmark Hill campus, and Figure 7 illustrates the expected maximal performance (Shannon capacity) of each of these links against the number of channels aggregated, under the assumption of non-contiguous aggregation. Table 2 provides equivalent experimental throughput results obtained using the WSDs, showing peak rates achieved for both UDP and TCP traffic, and how those rates compare with the theoretical capacity given in Figure 7. It is noted that the WSDs in all cases aggregated their maximum capability of 4 channels, and the UDP/TCP results were obtained using iPerf running directly on the WSDs at each end of the TVWS link, thereby removing spurious network/Internet effects.

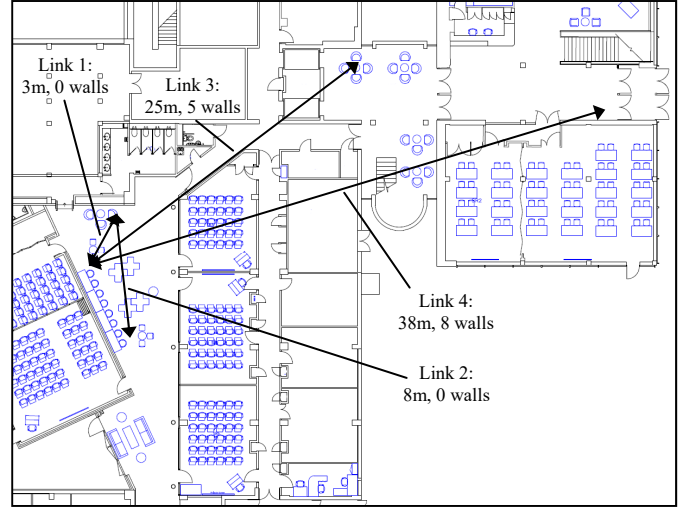


Fig. 6. The tested links in the King’s College London, Denmark Hill building, superimposed on a partial plan view of that floor of the building.

TABLE II: ACHIEVED PEAK RATE OF THE INTERDIGITAL DEVICES AGAINST MODELLED THEORETICAL CAPACITY

Link	Achieved peak rate (Mbps)				% Modelled theoretical capacity			
	Downlink		Uplink		Downlink		Uplink	
	UDP	TCP	UDP	TCP	UDP	TCP	UDP	TCP
1	35.0	12.5	23.9	11.9	5.7	2.0	3.9	1.9
2	34.2	15.9	34.8	15.7	6.5	2.3	4.4	2.2
3	33.6	16.8	29.0	15.2	9.7	3.5	6.6	3.3
4	33.0	14.6	24.2	7.0	12.9	4.6	8.8	4.4

Moreover, the comparison with theoretical performance is as a percentage of theoretical capacity for the 4 channel aggregation case in Figure 7, which respectively for Links 1 to 4 is 618 Mbps, 538 Mbps, 359 Mbps, and 270 Mbps.

Given the good TVWS availability of the Denmark Hill location, the theoretical aggregate capacity achieved increases proportionally with the number of channels aggregated, with a divergence of that relationship only beginning to be seen once a large number of channels are aggregated, typically around 15 channels. This divergence, as well as the differences among the capacities of the spectrum mask classes, is emphasized for the weaker received signal cases of Links 3 and 4.

The achieved throughput of the WSDs compares well with this, achieving an excellent percentage of the theoretical maximum capacity, noting many factors in a real system that suppress such a rate below the theoretical capacity, including the 802.11 PHY, RTS/CTS, and UDP/TCP protocols, among many others. This good performance is particularly noticed for Links 3 and 4, given that Links 1 and 2 were operating in a scenario of unrealistically strong signal power, outside of the intended range of the WSDs, hence being unable to take advantage of the high power through MCS. Moreover, for Links 1 and 2, the receive radios were somewhat saturated.

Finally, the measured propagation and capacity analyses have been compared against expected performance using the Yamada propagation model in Table 2. Results compare well, showing a difference of the propagation model from the actual

propagation measurements of between 0.5 and 8 dB. In terms of Shannon capacity, the difference of the propagation model based solution from the capacity based on measured propagation ranges from -6% for Link 1 to +20% for Link 4.

## V. CONCLUSION

The Ofcom TV White Spaces (TVWS) Pilot represents an important milestone in the realization of TVWS technology. This paper has described an aspect of our major trial within the Ofcom Pilot, namely, the utilization of InterDigital IEEE 802.11 White Space Devices (WSDs) aggregating up to four non-contiguous channels. This paper has described the equipment, provided key observations on contiguous and non-contiguous aggregation, and assessed performance of the WSDs under the UK/EU TVWS framework.

Aggregation in future wireless communications scenarios will be of increasing importance, due to fragmented spectrum. Moreover, aggregation in TVWS will often be essential in order to address the variability in performance achieved in TVWS, due to differences in allowed channels/powers and the interference that the WSDs see on channels, e.g., from other WSDs and in some cases from distant incumbent transmissions not meant to be covering the area. Aggregation in TVWS will also often be useful to match spectrum bandwidth to link demand. It is with such observations in mind that this work has been performed.

## ACKNOWLEDGMENT

This work has been supported by the ‘‘Spectrum Overlay through Aggregation of Heterogeneous Dispersed Bands’’ project, ICT-SOLDER, [www.ict-solder.eu](http://www.ict-solder.eu), the ‘‘ICT-ACROPOLIS Network of Excellence’’, [www.ict-acropolis.eu](http://www.ict-acropolis.eu), the H2020 5G-NORMA Project, and ELISA TEC2014-59255-C3-3-R.

## REFERENCES

- [1] FCC, ‘‘In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band, Second Memorandum, Opinion and Order,’’ September 2010 (see also Third Memorandum, Opinion and Order from April 2012).
- [2] Ofcom, ‘‘TV white spaces - A consultation on white space device requirements,’’ consultation, November 2012.
- [3] Ofcom, ‘‘TV white spaces - approach to coexistence,’’ consultation, September 2013 (an addendum to this from November 2013 also exists).
- [4] ETSI EN 301 598, ‘‘White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive,’’ v1.1.1, April 2014.
- [5] Ofcom TV White Spaces Pilot, <http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces/white-spaces-pilot>, accessed May 2014.
- [6] Ofcom, ‘‘Implementing TV White Spaces,’’ statement, February 2015, accessible at <http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement>, accessed May 2015.
- [7] InterDigital White Paper, ‘‘Dynamic Spectrum Management’’, accessible at [http://www.interdigital.com/wp-content/uploads/2012/10/InterDigital-DSM-White-Paper\\_Oct2012.pdf](http://www.interdigital.com/wp-content/uploads/2012/10/InterDigital-DSM-White-Paper_Oct2012.pdf), accessed February 2015.
- [8] J.Mack and J. Cartmell, ‘‘Field Trial Results for a Wi-Fi Based Spectrum Sharing Technology in TVWS,’’ IEEE LISAT 2014, May 2014.
- [9] O. Holland, *et al.*, ‘‘To White Space Or Not To White Space: That Is The Trial Within The Ofcom TV White Spaces Pilot,’’ IEEE DySPAN 2015, Stockholm, Sweden, September-October 2015.
- [10] W. Yamada, ..., O. Holland, *et al.*, ‘‘Indoor Propagation Model for TV White Space,’’ CROWNCOM 2014, Oulu, Finland, June 2014.

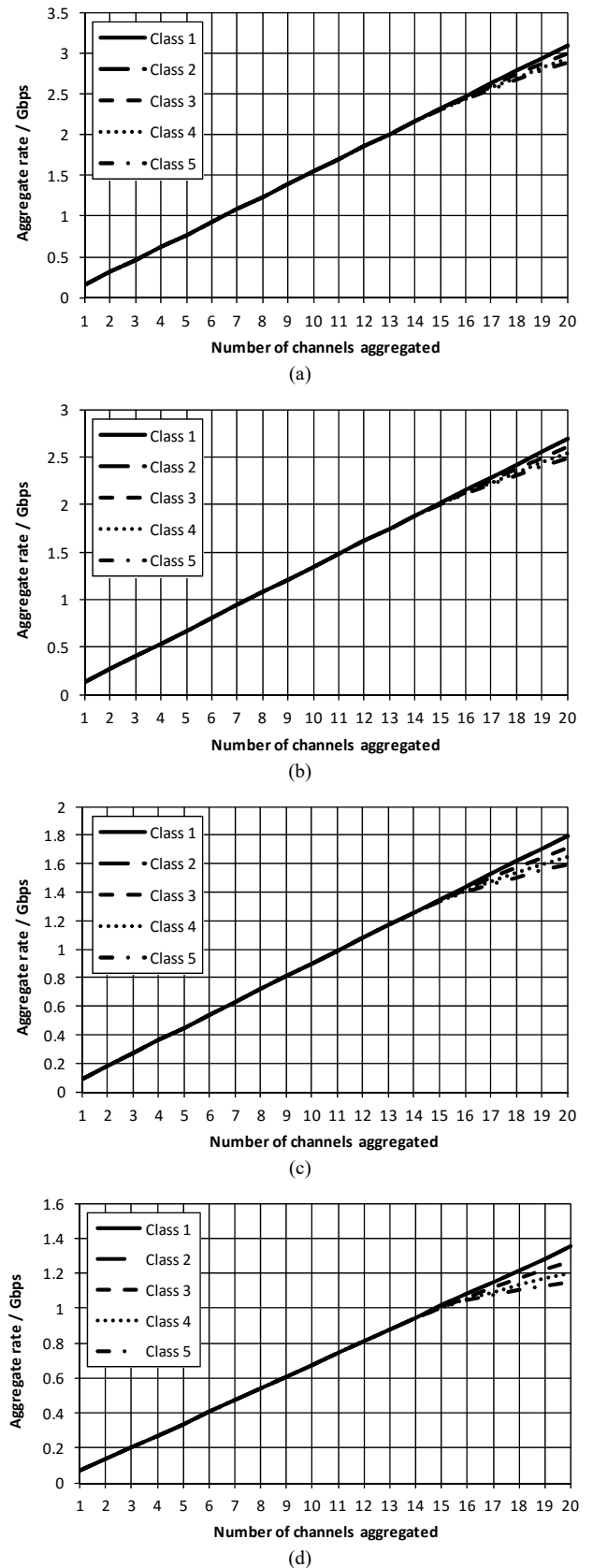


Fig. 7. Capacities of the tested links in the King’s College London, Denmark Hill building under contiguous or non-contiguous aggregation, for all Ofcom/ETSI mask classes: (a) Link 1, (b) Link 2, (c) Link 3, (d) Link 4.